ELECTROMIGRATION INDUCED RESISTANCE CHANGES IN PASSIVATED ALUMINUM THIN FILM CONDUCTORS

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ABSTRACT

The relative change in resistance due to electromigration was studied in thin (0.7 μm) film conductors of Al-0.5% Cu Alloy passivated with a 1 μm thick glass passivation using a sensitive AC bridge technique.[1] In contrast to previous experiments performed on unpassivated structures where a roughly linear resistance increase was observed, a saturation value for the resistance increase was observed which was seen to be a function of temperature and the applied current density. The results were found to be consistent with a Shatzkes and Lloyd electromigration model.[2,3]

INTRODUCTION

Resistance changes have often been used to characterize electromigration damage in thin film conductors.[4-6] Often, such measurements are difficult and sometimes inconclusive since there are a wide variety of factors which can affect the resistance of metallic conductors, unrelated to electromigration. To obviate these problems, a technique was developed where a special sample geometry is employed where two adjacent regions of a single sample serve as two legs of a Wheatstone Bridge. By passing current through only one of the legs and leaving the other unpowered, the resistance changes due to electromigration alone could be investigated. In principle (but, of course, not entirely in practice) all other effects, such as temperature variations and precipitation would not be incorporated into the data. In addition, the sensitive nature of the test allowed extremely small relative changes in the resistance, on the order of 1 ppm, to be examined.

Previous investigations[1] using this technique had revealed a roughly linear increase in resistance followed by a non-exponential decay when the power was turned off. The rate of increase was found to be thermally activated and approximately proportional to the applied current density. Of interest, and not as yet satisfactorily explained, was a strong variation from sample to sample in the activation energy for the resistance increase. The decay following the cessation of the current was not characterizable by a simple exponential. The decay was seen to be rather sluggish, requiring on the order of days at 200C for the excess resistance to be reduced to approximately 10% of its maximum value.

The present research extended the previous studies to include conductors covered by a strong passivation more representative of engineering materials. Since it has been demonstrated that passivations can increase the lifetime due to electromigration failure significantly, it was expected that the presence of passivation should alter the characteristics of the resistance behaviour as well.[7,8]

In addition, an attempt to explain the resistance increase in terms of an electromigration induced supersaturation of vacancies was made. The calculated values of excess vacancy concentration from the steady-state solution of the finite electromigration boundary value problem[9] agreed reasonably well with the values derived experimentally.

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EXPERIMENTAL DETAILS

The Al-1%Cu films were deposited on a Si substrate with a thin TiN layer at 425C with a magnetron sputtering system. The patterning was performed with a Reactive Ion Etching (RIE) technique. The structures were then covered with a 1 μm thick passivation layer (SiO_2). The test lines (two lines were arranged as a five point probe) were 1.5 μm wide, 0.7 μm thick and 300 μm long. The average grain size was approximately 4.3 μm.

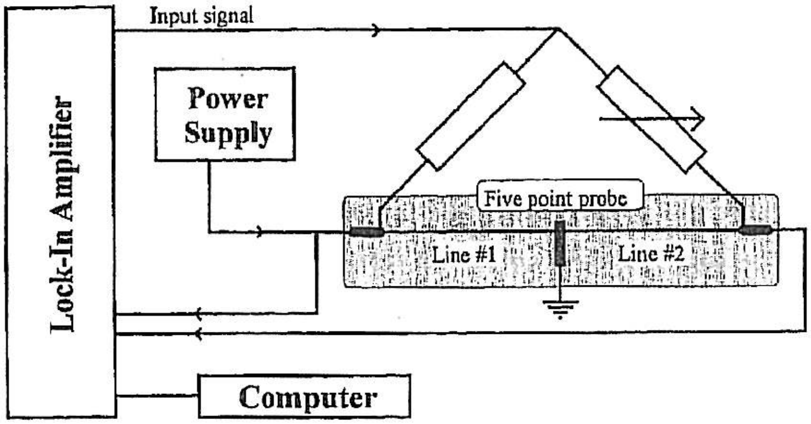

Figure 1: Schematic view of the circuit[10]

A schematic of the experimental apparatus is shown in figure 1. The five point probe was connected with two resistors to form a Wheatstone bridge. The bridge voltage was measured with a Lock-In Amplifier (EG&G PAR 5210) equipped with a built-in frequency generator. Only relative resistances could be detected (ΔR instead of R). For the electromigration stressing a DC current was superimposed with a HP 6181 C, DC Power Supply.

An advantage of the described method was extremely high resolution. The theoretical resolution was $1 \cdot 10^{-7}\ \Omega$ calculated with the parameters used in the experiments. Therefore it was possible to perform the experiments with relatively low current densities and/or low temperatures and, more importantly, to carry out several experiments on a single sample line (assuming no irreversible damage).

During this work, two kinds of experiments were performed using two different lines:

- Constant current density (1.9 MA/cm^2) and different temperatures (between 185°C and 212°C)
- Constant temperature (171°C) and different current densities (between 0.8 and 1.9 MA/cm^2)

RESULTS

The behavior exhibited an increase in resistance with time while high current was passed which appeared to approach an asymptotic value (fig. 2). Although the initial rate of increase was reasonably close to that previously observed, the apparent saturation value for the resistance at longer times has not been observed in unpassivated samples. Similar to previous experiments, when the current was turned off, a non-exponential decay was observed (fig. 2). The increase was seen to follow a relation of the form:

$$\Delta R = \Delta R^{\infty}\left[1 + \exp\left(\frac{t}{\tau}\right)\right] \qquad (1)$$

where ΔR^{∞} is the asymptotic value of the relative resistance and τ is a characteristic time for the increase. The data fit eqn. 1 reasonably well. A function with two exponentials in series fit the data only slightly better, but the use of a second term was not deemed appropriate without theoretical justification.

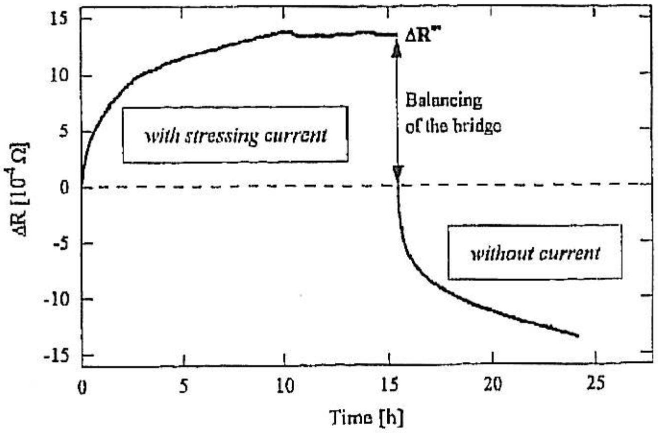

Figure 2: Typical curve with the increase in relative resistance during stressing and the decay after current switch-off

Both ΔR^{∞} and τ were seen to be both temperature and current density dependent. Both appeared to be thermally activated as depicted in figure 3. The activation energies for ΔR^{∞} and τ were calculated to be 0.6 and 0.54 eV respectively. The current density dependence for τ was not easily characterized. If we assume a power law fit, we obtain from a least squares analysis a current exponent of -1.2, which is not, at this time, accounted for theoretically. The current density dependence of ΔR^{∞} was seen to fit a theoretically suggested function of $[\exp(j) - 1]/j$ which will be discussed in the following section.

The decay following the end of stressing was also seen to be a function of temperature and current density. Curiously, in some cases, the ultimate decay of ΔR exceeded the increase during stressing. Since the resistance measurement is relative, this behavior suggests complementary processes of electromigration-induced damage and annealing acting in conjunction.

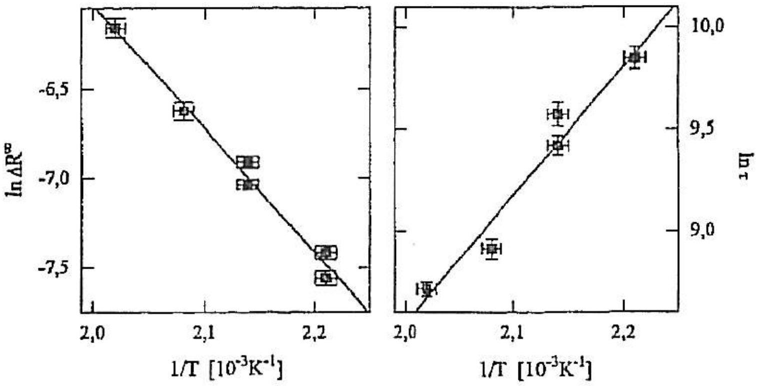

Figure 3: Arrhenius plots of ΔR^{∞} and τ

Because of the small relative resistance changes, being a maximum of about $30 \cdot 10^{-4}\,\Omega$, and almost entirely recoverable during subsequent unpowered annealing at the test temperature, it was believed that insufficient permanent damage was suffered by the samples as to preclude their subsequent use. In one case, however, a sharp irreversible increase in the relative resistance was observed, which it was decided should disqualify this sample from further investigation. Microscopic observation by high resolution optical and scanning microscopy revealed no visible damage to account for the resistance increase.

DISCUSSION

An important thing to keep in mind when considering the results of our experiments is that the increases in resistance measured by this technique are relative. Therefore, it is necessary for the interpretation of the ΔR curves to discuss possible processes that could change the line resistance in general and their influence on the relative resistance.

Temperature changes (in conventional resistance measurements on single lines they are the precision-limiting factor) do not play an important role in this method. Changes should be equal in each side of the bridge and the effects should therefore be absent from the data. Unfortunately, due to slight differences in initial resistance and temperature coefficient of resistivity, there is a slight temperature dependence of the bridge voltage, even without high current density stressing. These effects are small, however, on the order of 2 to 3 orders of magnitude less than simple resistance measurements.

Another source for resistance variations are precipitation reactions, but these should occur in both legs of the bridge equally. Under electromigration stressing however there are possibly differences because of the increased temperature on one side (due to Joule heating) or because of an electromigration-induced additional precipitation reaction.[11] The maximum size of this effect is hard to estimate.

Let us examine the increase in resistance according to a model where electromigration-induced vacancy migration can lead to accumulations at diffusion barriers such as contacts or discontinuities in the grain structure.[2,9] If we consider the fluxes due to the electromigration and a concentration gradient, the vacancy concentration can be expressed (with help of the continuity equation) as:

$$\frac{dC}{dt} = -D\frac{d^2C}{dx^2} + v\frac{dC}{dx} \tag{2}$$

$$\text{with} \quad \nu = \frac{DF}{kT}$$
$$\text{and} \quad F = z^{*}e\varrho j$$

where C is the vacancy concentration, t the time co-ordinate, D the diffusion coefficient, x the space co-ordinate, $z^{*}e$ the effective charge, ϱ the resistivity, j the current density and kT the thermal energy. Imposing the boundary conditions:

1. $C(x = -l, t) = C_0$, where C_0 is the vacancy concentration in thermal equilibrium and l the length of the conductor,
2. the total flux at $x = 0$ is zero (impermeable barrier),

the steady state solution ($dC/dt = 0$) for equation 2 is:

$$C = C_0 \exp\left[\frac{F}{kT}(x+l)\right] \qquad (3)$$

The attainment of steady state and, therefore a constant vacancy concentration, is a possible explanation for the appearance of a saturation value in the relative resistance (ΔR^{∞}).

The mean vacancy concentration $\bar{C}$ in the line (which is perhaps much higher than the thermal equilibrium value C_0) is obtainable with an integration of this concentration profile over the length l:

$$\bar{C} = C_0 \frac{kT}{lF}\left[\exp\left(\frac{lF}{kT}\right) - 1\right] \qquad (4)$$

The influence of an increased vacancy concentration on the electrical resistivity was measured by numerous authors, e.g. Simmons and Balluffi,[12] to be approximately 3 $\mu\Omega\, cm/\%\, vac.$

The total resistance increase due to an increase in vacancy concentration is then:

$$\Delta R^{\infty} = \frac{\xi C_0}{A}\frac{kT}{F}\left[\exp\left(\frac{lF}{kT}\right) - 1\right] \qquad (5)$$

where ξ is the value for the increase in resistivity due to vacancies and A the conductor cross sectional area. From this equation follows the dependency of ΔR^{∞} on current density j:

$$\Delta R^{\infty} \propto \frac{\exp(j) - 1}{j}$$

The comparison with the experimental results displays excellent agreement (figure 4). Unsolved so far is the dynamics of the vacancy increase (and the correlation with τ) and the influence of stresses on the maximum vacancy concentration. Further investigations are necessary to understand these interesting topics.

CONCLUSIONS

With application of a technique that allows highly accurate measurements of relative resistances, electromigration experiments at different temperatures and current densities were performed. An increase in relative resistance following an exponential function ends in a saturation value (ΔR^{∞}). ΔR^{∞} was temperature and current density dependent. The temperature dependence of ΔR^{∞} was explained with a vacancy accumulation model, which fits the experimental data.

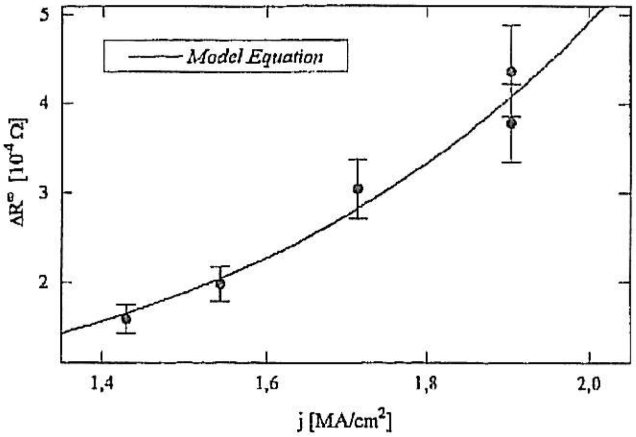

Figure 4: Plot of ΔR^∞ vs. j incl. the fit with the model equation

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